1/10 3 1 12 11 151

### SPACE SOLAR POWER TECHNOLOGY.DEMONSTRATION FOR LUNAR POLAR APPLICATIONS: LASER-PHOTOVOLTAIC WIRELESS POWER TRANSMISSION

Henley, M.W (1), Fikes, J.C. (2), Howell, J. (2), and Mankins, J.C. (3) (1) The Boeing Company, (2) NASA Marshall Space Flight Center, (3) NASA Headquarters

### **ABSTRACT**

Space Solar Power technology offers unique benefits for near-term NASA space science missions, which can mature this technology for other future applications. "Laser-Photo-Voltaic Wireless Power Transmission" (Laser-PV WPT) is a technology that uses a laser to beam power to a photovoltaic receiver, which converts the laser's light into electricity. Future Laser-PV WPT systems may beam power from Earth to satellites or large Space Solar Power satellites may beam power to Earth, perhaps supplementing terrestrial solar photo-voltaic receivers. In a near-term scientific mission to the moon, Laser-PV WPT can enable robotic operations in permanently shadowed lunar polar craters, which may contain ice. Ground-based technology demonstrations are proceeding, to mature the technology for this initial application, in the moon's polar regions.

### Introduction

technology, Power Solar Space including Laser-Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) may be used in a promising NASA space science application to power robot operations in dark craters at the moon's As Figure 1 North or South pole. illustrates, the moon's spin axis is nearly perpendicular to the plane of the ecliptic, so the sun never shines in the polar craters. Therefore, the craters are cold enough to preserve ice for billions of years, even in the hard vacuum of space. Radar from Arecibo and the Clementine spacecraft suggests the presence of ice in these regions, and data from the Lunar Prospector spacecraft confirms that a significant concentration of hydrogen (e.g, in frozen water) exists near the moon's poles. Ice deposits in lunar polar craters may record a long history of major astronomical events such as comet impacts on the moon, and potentially large impacts in the Earth's ocean's. Lunar polar ice could become a source of water, oxygen, and propellants for future human exploration and development of space. Laser-PV WPT can beam power from a permanently sunlit mountaintop at the moon's North or South Pole down into permanently shadowed craters, to enable long duration, "power-rich" robot operations that investigate the contents of lunar polar craters.

### Lunar Polar Mission Scenario

The general mission scenario for the exploration of these shadowed craters is illustrated in Figure 2. A lunar lander descends to a selected, continually sunlit region on a mountaintop near the moon's North or South Pole. The lander deploys a rover and photo-voltaic arrays are extended on both the rover and the lander. A laser system on the lander transmits power to the photovoltaic

receiver on the rover, initially checking out Laser-PV WPT operation and rover subsystems on the sunlit mountaintop. The rover then descends into shadowed regions along a pre-planned route using power beamed via laser from the lander. Deep in a permanently shadowed crater, the rover performs power-intensive scientific experiments, such as drilling, continuing to laser-PV WPT from the beamed mountaintop. This warmth. electricity, and provides illumination for a robotic rover to perform scientific experiments in cold, dark craters where other power sources are impractical. The concept of using Laser-PV WPT for such a mission to the moon's polar craters was first published by Canadian researchers (Enright and Carroll, 1997), and was independently suggested by researchers in Japan (Takeda and Kawashima, 1999) and in the USA (Potter, Willenberg, Henley, and Kent. 1999).

Prospector Lunar Data from the spectrometer neutron spacecraft's (Figure 3) indicate that hydrogen is concentrated at the moon's poles, presumably in the form of frozen volatile gasses, including water ice. Radar reflections suggest that water ice is indeed present in certain lunar polar craters. The total permanently shadowed area around the moon's North and South poles is estimated at 7,500 and 6,500 square kilometers, respectively (Bussey, 2002). Ice deposited in these regions over the last 2.5 billion years may a stratigraphic record contain tremendous value for Space Science, indicating the sequence, types, and sources of frozen volatiles, potentially asteroids, from comets, derived interplanetary dust, interstellar molecular clouds, solar wind, lunar vulcanism, and

production (Lucey, gas radiogenic Earth Science may also be 2002). comet fluxes and as advanced, significant Earth (ocean) impacts, both linked to major episodes of extinction of life on Earth, may be recorded in distinct strata in lunar polar ice deposits. resources at the moon's poles could provide water and air for human exploration and development of space, as well as rocket propellant for future space transportation.

Candidate mountain-top landing sites that appear to provide near-continuous sunlight and proximity to high hydrogen concentrations are also shown in figure A landing site must be chosen 3. carefully so that outpost remains in full sunlit over many months as the moon rotates once per month around it's Landing site slightly inclined axis. selection should also consider direct, communications with Earth, and local terrain features that might obstruct local communications and line-of-sight Wireless Power Transmission to a rover on the moon's surface.

Lunar topography near the North and South poles illustrated in Figure 4. Topographical features are significantly more pronounced at the South pole (at the edge of the Aitkin Basin, an area of particular scientific interest). In this region, the range in elevation is roughly 12 kilometers between the highest peaks and deepest craters.

The effects of local topography determine maximum laser range, as is illustrated in Figure 5. In this example, a WPT beam from a 1 km high mountain can travel 50 km before it is obstructed by the horizon. From the top of a 6 km high mountain, the WPT range increases

to 120 km before the beam grazes the horizon. The range can be extended further with laser projection into deeper craters. Relay mirrors are of particular interest as they can extend laser range and allow transmission of light into all areas of the lunar polar craters. Laser range may be also be extended by beaming between one mountain and another.

from range Approximate laser candidate mountain-top landing site near the moon's South pole is illustrated in Figure 6. This site, labeled as point E, allows direct communications with Earth as well as communications and laser 200 ranging up transmission kilometers, including access to the moon's South pole. Peaks identified as A, B, and C are closer to the South pole, but the moon's orbital motion leaves them without direct sunlight in portions of the "winter season" (when the pole is tilted one and a half degrees away from the sun). This region also looses direct line-of-sight communications to Earth for roughly half of each month. Peaks at the D and E appear to briefly shadow each other, at least for several hours each month during the South Pole's "winter" season. The peak labeled E has a more pronounced altitude gradient in the North-South direction, which is desired to minimize solar panel height to receive full sun during winter (deWeerd) and to enhance line-of-sight Laser-PV WPT and communications toward the Earth and the South pole. The peak F spot is high, and close to one of the deepest, most hydrogen-rich craters, but it is too far from the South pole to be in constant sunlight.

Figure 7 illustrates an example lunar roving vehicle path in the vicinity of the

moon's South pole. The rover's primary mission proceeds from an Space Solar Power outpost on Peak E, down into a hydrogen-rich spot labelled G, deep in the bottom of the deepest crater. The rover's path covers a traverse distance of approximately 200 km, with a 12 km decrease in altitude. Within this deep crater, Laser-PV WPT, with a line-ofsight range close to 100 km, provides the rover's only power source. secondary mission objective, following thorough investigation of the crater, the rover may traverse upward, out of the crater, to reach and research other potentially visiting locations, geographic South Pole and perhaps even returning to the original point of departure.

A large rover is needed to perform such a long distance traverse. Due to the large Laser-PV WPT ranges involved, a fairly large photo-voltaic receiver will be needed, also implying a fairly large rover. NASA's Marshall Space Flight Boeing have already Center and developed a large rover, the Apollo Lunar Roving Vehicle (LRV, and flightproven it over significant ranges on the moon (Figure 8). LRV units remaining from Apollo could even, potentially, be modified to perform the mission described here.

### **Technology Development**

Technology demonstration activities are proceeding to demonstrate Laser-PV WPT technology on Earth, in advance of a lunar polar mission, as a cooperative effort between Government, aerospace industry, and academic institutions. Harvey Mudd College has developed a specialized laser beam expander (Figure 9) for precise beam pointing and focusing, allowing long distance power

transmission. Initial tests of this laser transmitter over modest ranges (Figure 10) found minor imperfections in the primary mirror, but managed to maintain near constant beam dimensions over a one kilometer range. For longer range demonstrations (on Earth), ground atmospheric transmission issues become more significant and laser wavelengths must be selected accordingly (Figure 11). Using an 830 nm laser wavelength (with high atmospheric transmissivity), and Galium Arsenide photovoltaic cells, the University of Colorado-Boulder has achieved close to 70% percent efficiency in converting laser light into electricity [34% efficiency was (Figure 12). achieved in similar Japanese research using an 805.8 nm wavelength and Silicon photovoltaic cells (Takeda and Kawashima, 1999)]. The University of Colorado-Boulder has also developed prototype photo-voltaic receivers for small remotely controlled rovers (Figure 13), including a beam-concentrating reflector, designed to efficiently receive an expanded laser beam with a gaussian intensity profile (Figure 14). Carnegie Mellon University has developed a larger photovoltaic powered rover for lunar polar technology demonstrations (Figure 15), and is assessing system Laser-PV for modifications research purposes. NASA and Boeing are integrating these components for ground technology demonstrations.

Ground testing of Laser-PV WPT for lunar polar applications is proceeding in the state of Hawaii (Figures 16). State-of-the-art laser research facilities exist on top of Mount Haleakala at NASA's Lunar Ranging Experiment (LURE) observatory and the Air Force Maui Optical and Supercomputing (AMOS) site, and this geometry, beaming down

from a mountaintop, is similar to the geometry of the lunar polar technology application. Unique long-range power transmission experiments are possible here, similar to the ranges expected for lunar polar Laser-PV WPT applications, and the air is exceptionally clear, effects. atmospheric minimizing Candidate power receiving areas include local terrain that is similar to lunar terrain, including finely divided soils, and craters (of volcanic origin, rather Apollo LRV than meteoritic origin). operations were previously tested in this area, and it is a logical location for further research and development of a large lunar rover.

### Conclusion

Space Solar power technology, including Wireless power laser-Photo-Voltaic Transmission, is enabling for near term robotic missions to investigate potential ice deposits in lunar polar craters. Technologies demonstrated and matured via lunar polar applications can also be used in other NASA science missions (Valles Marineris, Phobos, Deimos, Mercury's poles, asteroids, etc.) and in future large-scale SSP systems to beam energy from space to Earth. Continuing activities should increase transmission distances, power levels, and efficiencies, in preparation for a near-term space science and technology demonstration mission.

### References

Alvarez, L.W., Alvarez, W., Asaro, F., and Michel, H.V.. "Extraterrestrial Cause for the Cretaceous-Tertiary Extinction: Experimental Results and Theoretical Interpretation" *Science*, Vol. 208 (1980), pp. 1095-1108

Alvarez, W. "Toward a Theory of Impact Crises," *EOS*, Vol. 67, No. 35, pp. 649-658, Sept. 2, 1986

Armstrong, J.C., Wells, L.E., Kress, M., and Gonzalez, G., The Moon: A Repository for Ancient Planetary Samples, Workshop on The Moon Beyond 2002 September 12–14, 2002, Taos, New Mexico http://www.lpi.usra.edu/meetings/moon2002/pdf/program.pdf

Arnold, James R. "Ice in the Lunar Polar Regions," Journal of Geophysical Research, Vol. 84, B10, pp. 5659-5668, Sept. 10, 1979

Britt, Robert Roy; Moon Holds Earth's Ancient Secrets, space.com, 23 July 2002, [http://www.space.com/scienceastronomy/moon\_earth\_020723.html]

Bussey, D. B. J., Robinson, M. S., Edwards, K., Spudis, P., Lucey, P., and Steutel,, Permanent Shadow in Lunar Simple Craters, Workshop on The Moon Beyond 2002 September 12–14, 2002, Taos, New Mexico, http://www.lpi.usra.edu/meetings/moon2002/pdf/program.pdf

Butler, B., J., Volatiles at the Poles of the Moon, Workshop on The Moon Beyond 2002 September 12–14, 2002, Taos, New Mexico,

http://www.lpi.usra.edu/meetings/moon2002/pdf/program.pdf

Crider, D. H. and Vondrak, R.R., Comparison of Possible Sources of Hydrogen in Lunar Polar Deposits [#1369], Lunar & Planetary Science XXXI Conference, Spring, 2000 Crider, D. H. and Vondrak, R.R., Modeling the Stability of Volatile Deposits in Lunar Cold Traps, Workshop on The Moon Beyond 2002 September 12–14, 2002, Taos, New Mexico,

http://www.lpi.usra.edu/meetings/moon2002/pdf/3006.pdf

De Weerd, Jeroen F., Kruijff, Michiel, Ockels, Wubbo J., Search for Eternally Sunlit Areas at the Lunar South Pole from Recent Data: New Indications Found, IAF-98-Q.4.07, 49<sup>th</sup> International Astronautical Congress, Sept 28-Oct 2, 1998, Melbourne, Australia

Duke, Michael, Sample Return from South Pole Aitkin Basin, Workshop on The Moon Beyond 2002 September 12–14, 2002, Taos, New Mexico, http://www.lpi.usra.edu/meetings/moon2002 /pdf/program.pdf

Enright, John, and Carroll, Kieran; Laser Power Beaming for Lunar Pole Exploration, SPS '97: Space Power Systems for Humanity, Montreal, 1997

Feldman, W. C., Maurice, S., Binder, A. B., Barraclough, B. L., Elphic, R. C., and Lawrence, D. J., Fluxes of fast and epithermal neutrons from lunar prospector: evidence for water ice at the lunar poles: *Science*, 281, pp. 1496-1500, 1998

Feldman, W.C., Lawrence, D.J., Elphic, R.C., Barraclough, B.L., Maurice, S., Genetay, I., and Binder, A.B., Polar Hydrogen Deposits on the Moon, Journal of Geophysical Research, V105E2, pp. 4175-4195, February 25, 2000

Hut, P., et al. Comet Showers as a Cause of Mass Extinctions, in *Nature*, Vol. 329 (1987), pp. 118-126.

"Japan-Watch"- Laser Powers Lunar Rover Model, in *Laser Focus World*, August 2002, p. 56-57 (reprint from O plus E Magazine, Tokyo)

[http://lfw.pennnet.com/Articles/Article\_Dis

play.cfm?Section=Articles&Subsection=Display&Article\_ID=150980]

Kawashima, Nobuki; The Importance of Development of a Rover for the Direct Confirmation of the Existence of Ice on the Moon, in *Transactions of the Japan Society for Aeronautical and Space Sciences*, May, 2002, v. 43, n. 139, pp. 34-35

Lanzerotti, L.J., W.L. Brown, and R.E. Johnson, Ice in the Polar Regions of the Moon, Journal of Geophysical Research, Vol. 86, B5 (May 10, 1981), pp. 3949-3950

Lawrence, D. and Duke, M. (Chairmen) Workshop on The Moon Beyond 2002 September 12–14, 2002, Taos, New Mexico. [http://www.lpi.usra.edu/meetings/moon200 2/pdf/program.pdf]

Luce, Rick and Michael, Sherif, Laser Beaming Experiment, presented at the AMOS Technical Conference, Maui, Hawaii, 17 Sept, 2002

Lucey, P. G., Polar Night, A Mission to the Lunar Poles, Workshop on The Moon Beyond 2002 September 12–14, 2002, Taos, New Mexico, http://www.lpi.usra.edu/meetings/moon2002 /pdf/3067.pdf

Margot, J-L. Campbell, D.B., Jurgens, R.F., and Slade, M. A., Digital Elevation Models of the Moon from Earth Based Radar Interferometry, IEEE Transactions of Geoscience and Remote Sensing, Vol. 38, No. 2, March, 2000

Margot, J.L., D.B. Campbell, R.F. Jurgens, and M.A. Slade. Topography of the Lunar Poles from Radar Interferometry: A Survey of Cold Traps Locations. Science, vol. 284, 4 June, pp. 1658-1660, 1999

Moore, Taylor, Renewed Interest in Space Solar Power, EPRI Journal, pp. 6-17, Spring, 2000 NASA, Final Proceedings of the Solar Power Satellite Program Review, Conf-800491 July 1980

NASA, Space Solar Power: A Fresh Look at the Feasibility of Generating Solar Power in Space for Use on Earth, NASA report SAIC-97/1005, Contract NAS3-26565, Task Order 9, April, 1997

Potter, S., Willenberg, H., Henley, M., and Kent, S. Science Mission Opportunities Using Space Solar Power Technology, IAF-99-R.3.07, 50<sup>th</sup> IAF Congress, Oct. 1999, Amsterdam, The Netherlands

Seigfried, W. Lunar Base Development Missions. 49th International Astronautical Congress, Sept. 28 to Oct. 2, 1998.

Stacy N. J. S., Campbell, D. B., and Ford, P. G., Arecibo radar mapping of the lunar poles: *Science*, 276, 1527-1530, 1997

Takeda, Kazuya, and Kawashima, Nobuki, "Development of a Diode Laser Energy Transmission System Model to the Moon Pole Ice Investigation Rover", Eighteeenth ISAS Space Energy Symposium; pp. 38-42, February 16, 1999 (note: paper is written in Japanese, abstract in English).

Watson, K., B.C. Murray, and H. Brown. The Behavior of Volatiles on the Lunar Surface, Journal of Geophysical Research, Vol. 66 (1961), p. 3033

Williams, M.D., De Young, R.J., Schuster, G.L., Choi, S.H., Dagle, J.E., Coomes, E. P. Antoniak, Z. I., Bamberer, J. M., Bates, J. M., Chiu, M. A., Dodge, R. E., and Wise, J. A., Power Transmission by Laser Beam from Lunar –Synchronous Satellite; NASA Technical Memorandum 4496, November, 1993

## Space Solar Power Technology Demonstration for Lunar Polar Applications

IAC-02-r4.04

Henley, M.W (1), Fikes, J.C. (2), Howell, J. (2), and Mankins, J.C. (3)

(1) The Boeing Company, (2) NASA Marshall Space Flight Center, (3) NASA Headquarters

World Space Congress Houston, Texas

October, 2002

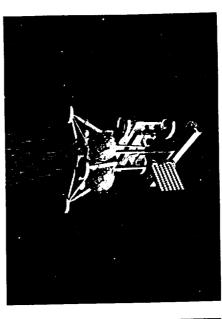


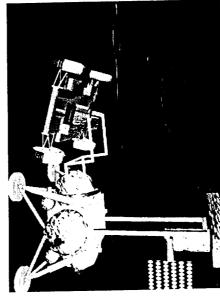
### Technology Demonstration for Lunar Polar Applications Space Solar Power

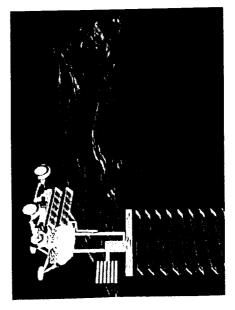
- PV WPT) is being developed for lunar polar applications by Boeing and Technology for Laser-Photo-Voltaic Wireless Power Transmission (Laser-NASA Marshall Space Flight Center
- A lunar polar mission could demonstrate and validate Laser-PV WPT and shadowed craters that are believed to contain ice other SSP technologies, while enabling access to cold, permanently
- Craters may hold frozen water and other volatiles deposited over billions of years, recording prior impact events on the moon (and Earth)
- light, when required, to explore a wide range of lunar polar terrain A photo-voltaic-powered rover could use sunlight, when available, and laser
- South Pole-Aitkin Basin has high priority for Space Science The National Research Council recently found that a mission to the moon's

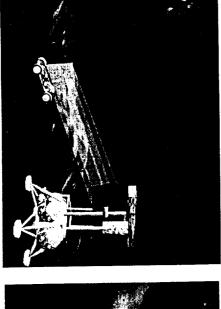
For Luman Pollan Alphilications Technology Demonstration Space Solar Power

# Lunar Polar Technology Flight Demonstration Overview of Mission Concept

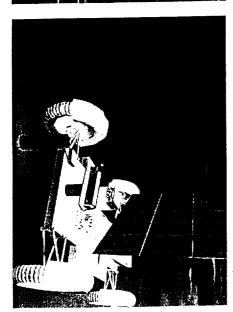












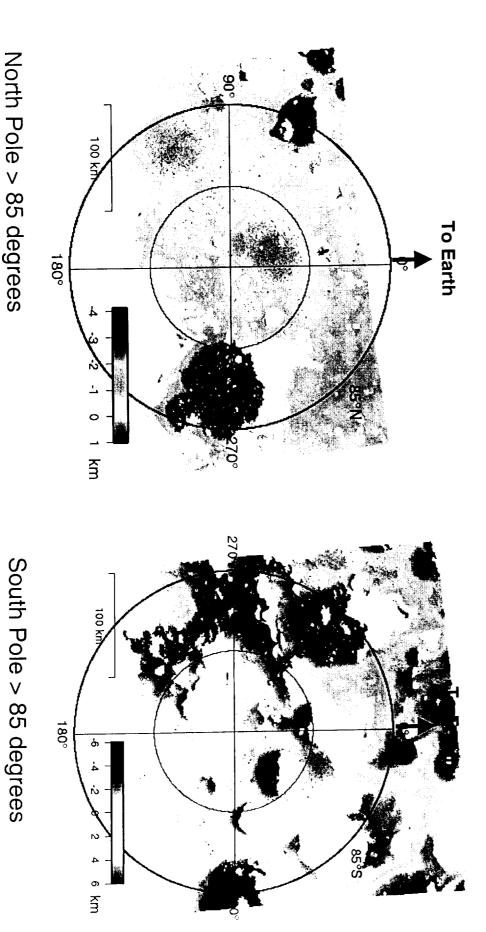
### from Lunar Prospector Spacecraft Neutron Spectrometer Data

Dark BLUE indicates highest Hydrogen concentration

North Pole > 85 degrees **LETTERS** indicate candidate Laser-PV WPT sites South Pole > 85 degrees

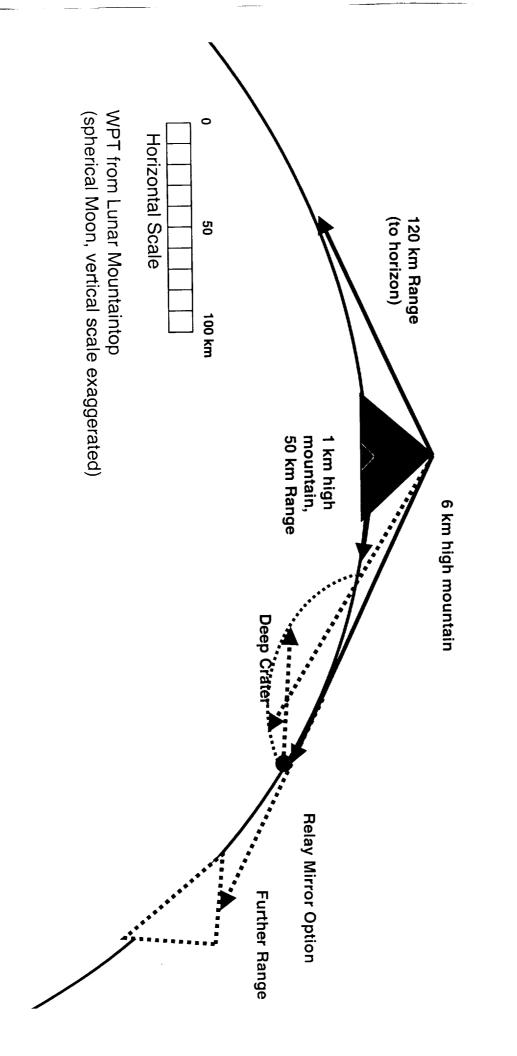
# Radar-Derived Topography of the Moon's North and South Poles

Note Difference in Vertical Scale!!!

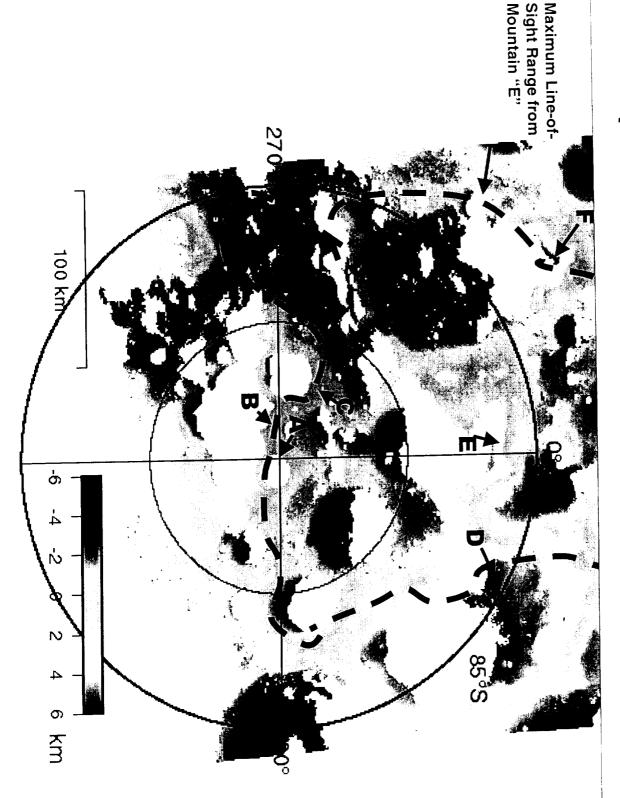


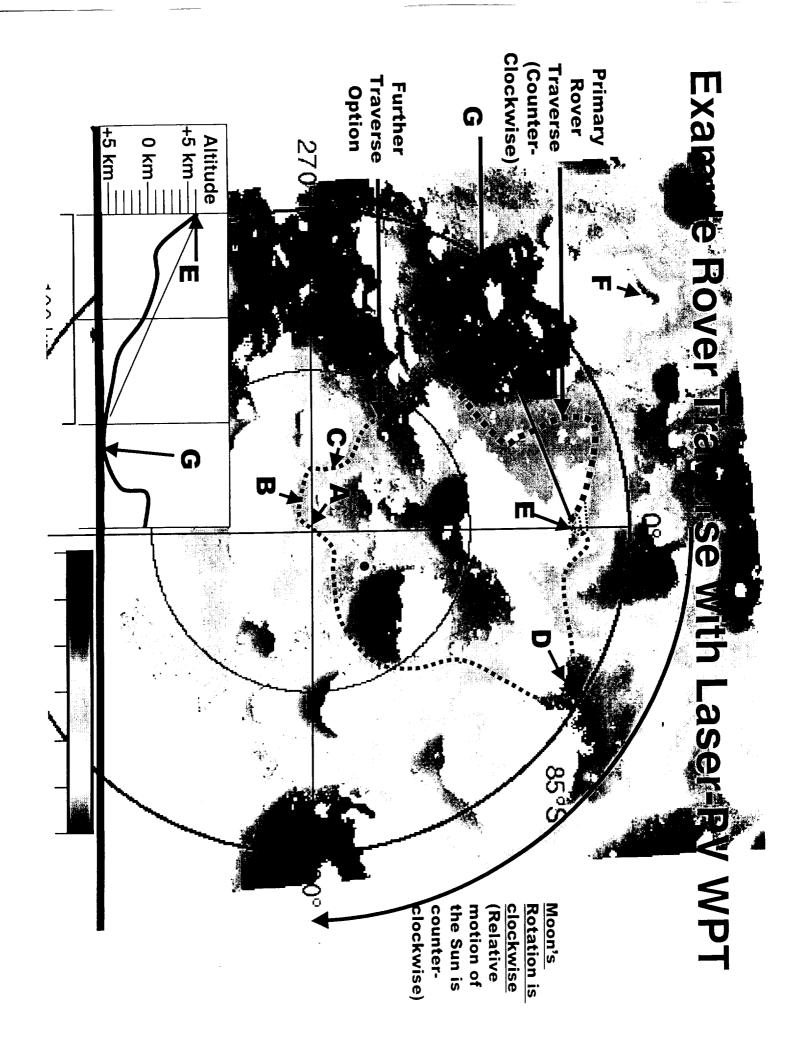
# Laser Range Depends on Topography

Transmitter on lunar mountain could beam power > 100 km



## Laser Range from Example Mountain-Top (Direct Line-of-Sight from Point E)





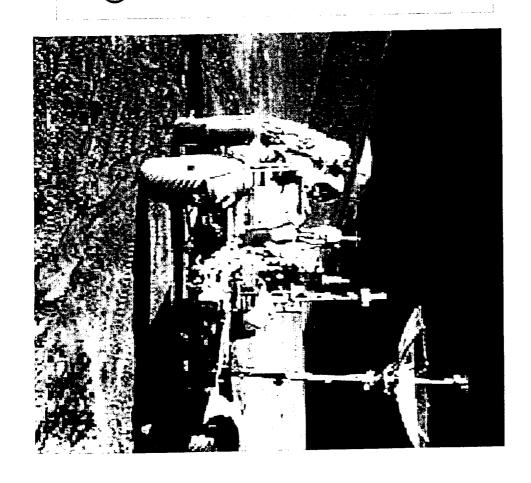
## Candidate for Lunar Laser-PV WPT Mission Apollo Lunar Roving Vehicle (LRV):

### Key Features:

Flight-proven on the Moon
2 flight-qualified units still exist
Long Distance Roving Capability
Large Platform for WPT Receiver

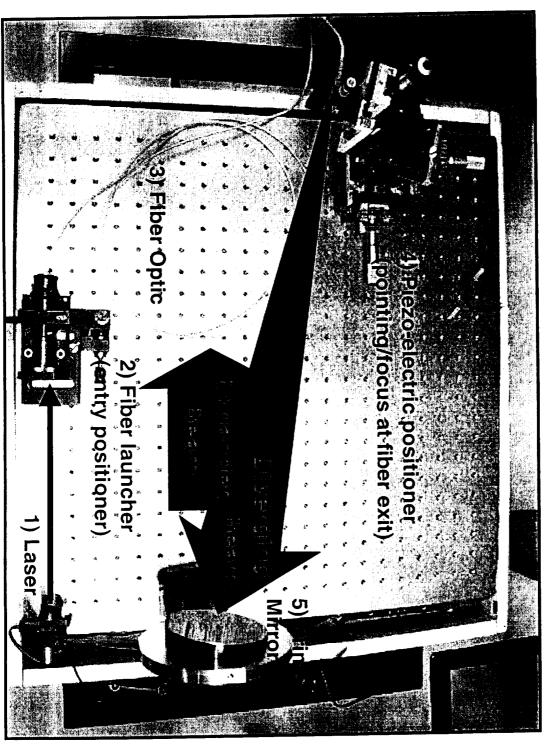
### Potential LRV Modifications

Large Photo-Voltaic Panel
Revise Batteries (rechargeable)
Revise Deployment System
Revise Data / Comm. Interfaces
Delete Crew Interfaces (optional)
Add Teleoperation Capability
Extend Range of Ops (TBD x 100 km)
Requalify for Low T Ops (~100 Kelvin)
Add Scientific Payload Interfaces





### **Experimental Laser Transmitter** (Harvey Mudd College)





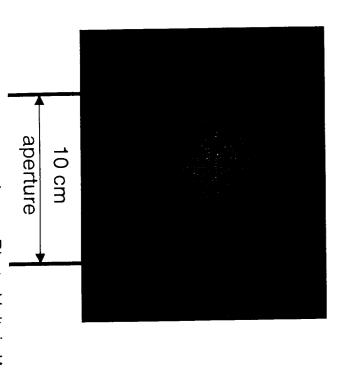


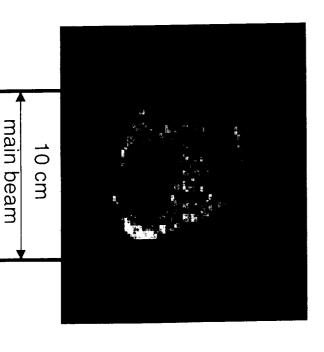
### Short-Range (~ 1 meter)

 Minor imperfections from diamond-cut primary mirror (corrected by replacing mirror)

### Mid-Range (~ 1 kilometer)

Image distortion due to 3 hole mounting of primary mirror (corrected by replacing mirror)











### Atmospheric Transmission Issues for **Ground Technology Demonstrations**

significant in WPT demos Air Mass is long distance

wavelength Scattering is selection Absorption influences

wavelengths shorter Shimmering effects may call for active

compensation

250

5 8

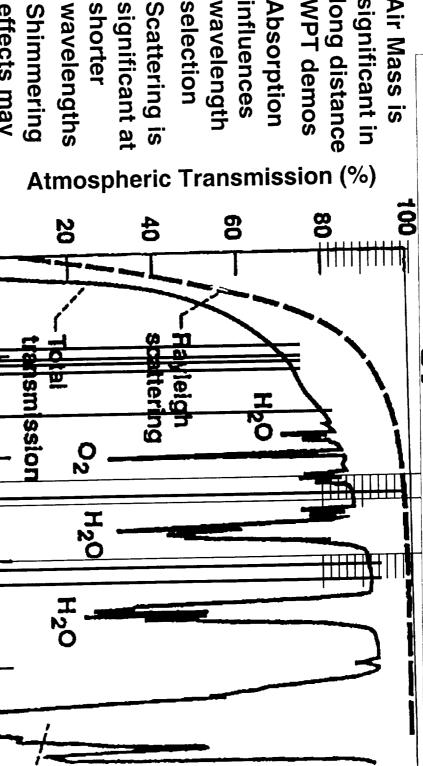
750

ppo!

1250

1500

H<sub>2</sub>O



Laser-Photo-Voltaic Wireless Power Transmission

Mrgon (488 & 514 nm)

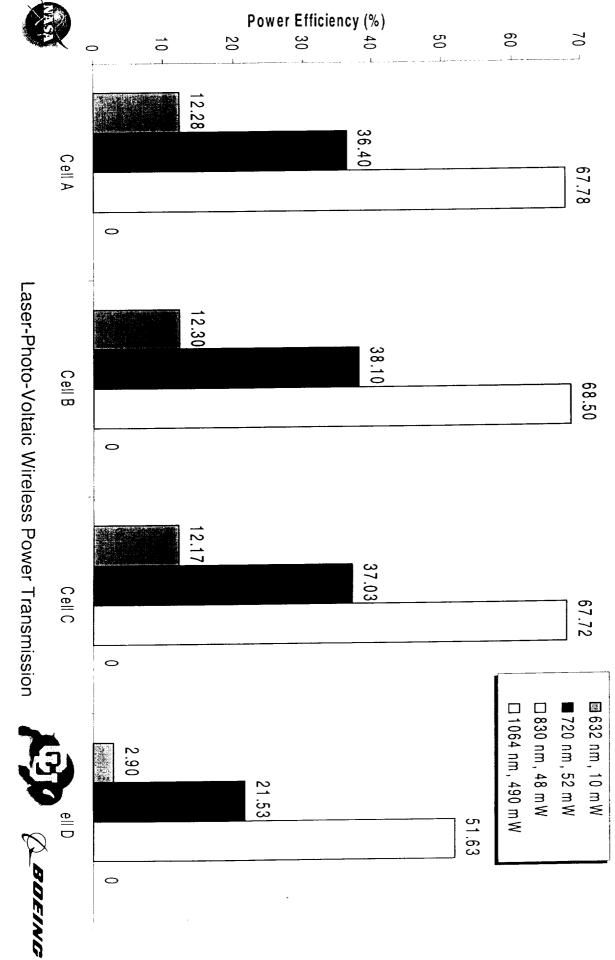
| (647 nm) (830 nm) Yb:YAG (1030 nm) | Doubled YAG

Nd:YAG (1064 nm)

Wavelength, hm Krypton Diode No



# Gallium Arsenide Photo-Voltaic Cell Efficiency vs. Laser Wavelength (U. Colorado-Boulder)

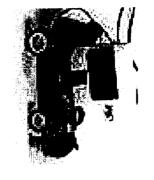


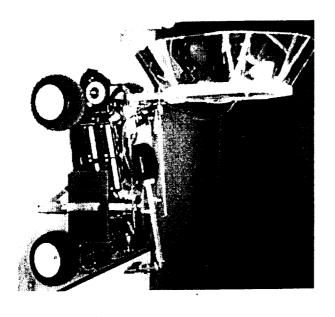
### Experimental Laser Receivers & Rovers (University of Colorado at Boulder)

Moon/Mars Rover (2000-2001) Proj<u>ect LaMaR</u>:Laser-powered Initial Laser-PV WPT efficiency tests

Small rover with photovoltaic cells

Project MEDL:Moon/Mars Explorer of On-board display (Current, Voltage, Temp.) Photovoltaic Array surrounded by reflector Radio transmission of visual data from rover Larger radio-controlled rove Dark Landscapes (2001-2002) Condition monitoring Rover teleoperation Concentrates light on PV array Evens Gaussian laser intensity profile





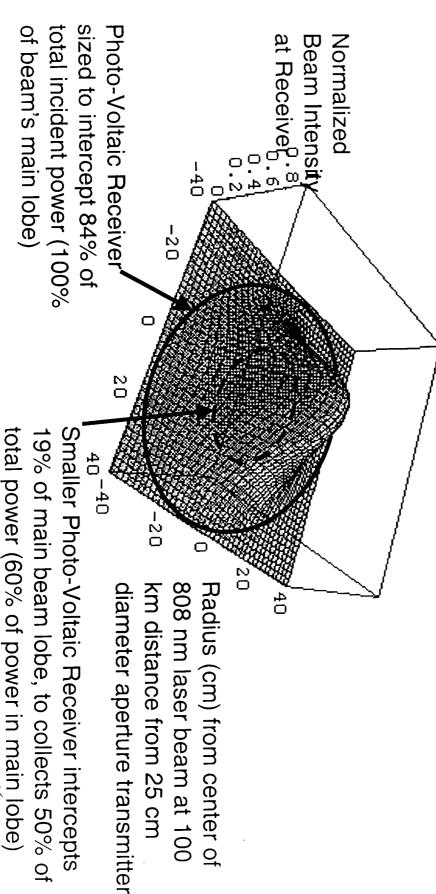






# Gaussian Laser Beam Intensity Distribution

- Smaller receiver, allowing beam spill-over, may be advantageous for lunar polar applications (<1/5 the PV area for >1/2 the power output)
- More even illumination of photo-voltaic array improves efficiency

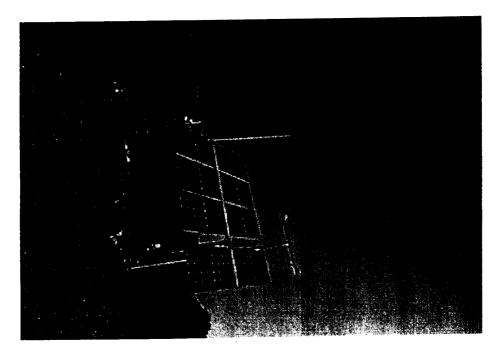




PBOEING

## Photo-Voltaic Rover for Further Research (Carnegie Mellon University)

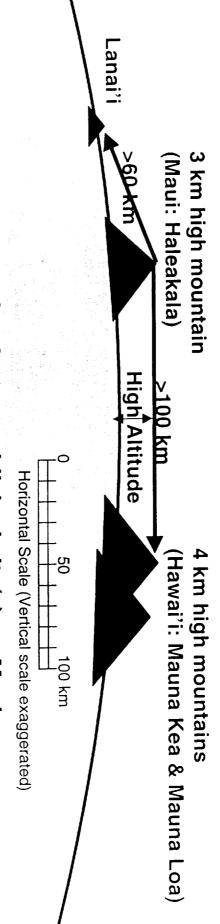
- Developed by the Robotics Institute at Carnegie Mellon University to demonstrate technology for a future Lunar Polar mission
- Circumnavigated Haughton Crater in the Canadian Arctic in Summer, 2001
- Autonomous ops in constant sunlight
- Currently under study for potential near-term applications in ground demonstrations of Laser-Photovoltaic wireless power transmission
- Large, cooperative target for long distances
- Possible system revisions (e.g., PV receiver)







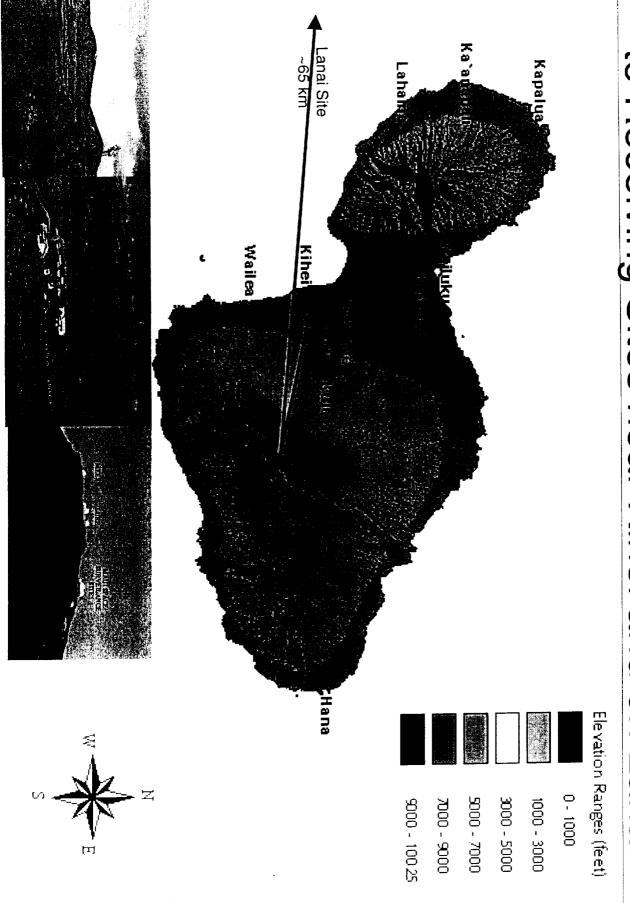
# for Technology Demonstration and Lunar Mission Simulation Wireless Optical Near-field Directed Energy Relay



# Laser Power Transmission from established site(s) on Maui

- Air Force Maui Optical and Supercomputing (AMOS) Site
- World-class laser facilities with large, high quality optics
- NASA Lunar Ranging Experiment (LURE) Observatory
- Laser telescope operated by the University of Hawaii
- Photo-Voltaic Power Reception at site(s) on Maui, Lanai, or Hawaii
- Barren terrain, similar to moonscape, can simulate mission operations
- Large areas have fine volcanic ash soils (similar to lunar regolith)
- Small craters exist at volcanic vents
- Candidate site on Hawaii was used to test Apollo rover)
- Similar to lunar polar geometry, laser beams down from mountaintop
- Relatively low humidity; Excellent night-time visibility
- Potential for End-to End technology demonstration / validation

## Overview of Laser Beaming from Haleakala to Receiving Sites near Kihei and on Lanai





- can enable access to permanently shadowed craters Laser-Photo-Voltaic Wireless Power Transmission near the moon's North and South Poles
- Lunar application can matures Laser-PV WPT technology while investigating ice deposits with high value for Space Science and Human Exploration and Development of Space
- Ground demonstration is prerequisite for Flight demo
- Current Status: Small scale benchtop tests initiated at AMOS
- Next Step: Initiate power beaming over modest distances
- Potential Future Steps:
- Increase range, efficiency, apertures and power levels
- End-to-end technology demonstration (power from sunlight)
- Test prototype flight hardware in simulated mission operations
- Perform lunar mission (technology flight demonstration)



